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Glider-based Observations of Kuroshio Seasonal Variability and Loop-Current Intrusion into the South China Sea

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Award Number: N00014-06-1-0776
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LONG-TERM GOALS

Two long-term goals, one technical and one scientific motivate this project. The technical goal is to advance techniques of observing the upper ocean, in this case proving the utility of underwater gliders. The scientific goal is to understand the effects of mesoscale processes on larger scales such as the general circulation, and on smaller scales such as internal waves.

OBJECTIVES

The primary technical objective is to demonstrate the use of a glider fleet in sampling a strong boundary current where the flow is often stronger than the glider can overcome.

The general scientific objective is to quantify the spatial structure and temporal evolution of the southern reaches of the Kuroshio. We plan to characterize the annual cycle of the Kuroshio and its associated mesoscale field. A next objective is to observe and quantify intrusions of the Kuroshio through the Luzon Strait. These mesoscale observations then provide the background on which strong nonlinear internal waves propagate.

APPROACH

A novel application of maturing autonomous glider technologies has allowed repeated occupation of multiple sections along approximately 1000 km of the Kuroshio's pathway (from Luzon to Ryukyu Islands). Gliders cycle from the surface to 1000 m at roughly six-hour intervals traveling 6 km through the water, traversing approximately 2000-3000 km over the course of a 3-4 month deployment. Observed variables include pressure, temperature, salinity, depth-averaged velocity, and optical properties. Gliders steer through the water by controlling attitude (pitch and roll) and can thus navigate between waypoints to execute survey patterns; or they hold station while profiling and collect Eulerian time series as a 'virtual mooring'. Gliders are commanded remotely and report their measurements via Iridium satellite telephone at the conclusion of each dive. The vehicles also archive all data to onboard storage for delayed mode transmission or post-recovery interrogation. They use GPS navigation at the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **Glider-based Observations of Kuroshio Seasonal Variability and Loop-Current Intrusion into the South China Sea**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California San Diego,Scripps Institution of Oceanography,Mail Code 0213,La Jolla,CA,92093-0213**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**4**	

sea surface to dead reckon toward commanded targets. Navigation and knowledge of vehicle buoyancy and pitch angle allows estimation of depth-averaged current and suitably energetic vertical velocity fluctuations. Gliders have been deployed and recovered from a wide range of platforms including small rubber boats, chartered fishing vessels and large research ships.

Craig Lee of University of Washington is an equal partner in this collaborative project. All operations will be joint efforts, with the expectation that collaboration will produce efficiencies. David Tang of Taiwan has aided with local logistics, including providing a vessel for glider recovery.

WORK COMPLETED

Field operations in the Kuroshio were completed successfully during the past year. Thirteen gliders (7 Sprays from SIO and 6 Seagliders from UW) were deployed and recovered starting in April 2007 and ending in June 2008. Turnarounds were done in July 2007, October 2007, and March 2008. Over 5000 dives to as deep as 1000 m were done as the gliders covered over 20,000 km in more than 1000 glider-days.

Most of the gliders followed a zig-zag path northward, often in formation separated along the path by 3-7 days. The separation in space and time allows multiple occupations of sections to observe the evolution of mesoscale features. Such statistics as the autocovariance and structure function have been calculated. Three gliders crossed the Kuroshio through the Luzon Strait. One of these gliders made two two-week-long time-series stations in the path of tidal internal waves generated at the Strait.

Work is proceeding on a pilot project to observe the North Equatorial Current (NEC) and the Mindanao Current. Two Sprays were deployed from Palau in June 2009, one that proceeded northward across the NEC, and one that headed westward towards the MC. These gliders were recovered in September 2009, when two more gliders were deployed.

We attended a planning meeting November 2006 in Taiwan to consult with international colleagues. Preliminary results were presented a meeting September 2007 in Alaska. Presentations were made at the 2008 Ocean Sciences Meeting in Florida. Two presentations were made at the 2008 Fall AGU Meeting. One presentation is planned at the 2010 Ocean Sciences Meeting.

RESULTS

The technical objective of demonstrating the utility of a glider fleet in a region of strong currents has been achieved. Depth-average currents greater than 0.25 m/s (glider speed through the water) occurred 5-30% of the time depending on the deployment. In the presence of these strong flows, we were able to hit desired waypoints. Furthermore, we were able to cross the Kuroshio through the Luzon Strait with three separate gliders.

Preliminary scientifc results emphasize the mesoscale variability, which is often so strong that it obscures the northward flowing Kuroshio. A salinity maximum is observed at 100-200 m, strongest in the region of the Kuroshio. Low salinity intermediate water near 500 m depth is found to have structure on roughly 50 km horizontal scales. Consecutive sections, occupied weeks apart, show the evolution of salinity anomalies in this intermediate layer. The Kuroshio, and associated mesoscale, is observed to strengthen as it flows northward. Strong stirring is evident in the salinity extrema. This

feature is consistent with the relatively young age of the water in the extrema relative to the inflection level between.

Two time-series stations showed the steepening of large-amplitude (over 100 m) internal waves as they propagated westward. The glider proved to be a surprisingly good platform for observing these nonlinear internal waves. In this application, the glider profiled from the surface to 500 m every 3 hours. Vertical velocities of over 0.1 m/s were observed as the glider's ascent was occassionally reversed during strong downwelling events. When the nonlinear internal waves were observed, they were found at a consistent daily interval, consistent with moored results from the area.

The first results from a glider crossing of the NEC (Figure 1) show some of the characteristics of the region. A wedge of warm, salty water is associated with the westward flowing NEC. Westward flow is mostly confined to shallow waters including this salty water and the mixed layer above. The NEC is apparent from roughly 8°N to 15°N. Two crossing of the NEC were made, and averaging these yields a transport of 49 Sv, consistent with previous estimates. Gliders have the promise of resolving spatial and temporal variability of the NEC and its transport in a way not previously possible.

IMPACT/APPLICATIONS

The demonstration of glider utility in a strong western boundary current should influence future glider operations in similarly strong flows.

The use of gliders to hold station and observe internal waves may prove to have some advantages, as the gliders can be positioned interactively to be in path of the waves.

Gliders are showing potential for the sustained observation of major ocean currents.

RELATED PROJECTS

This project takes advantage of glider technology that has been developed through grants from several agencies including ONR, NSF, and NOAA.

PUBLICATIONS

Van Uffelen, L. J., P. F. Worcester, M. A. Dzieciuch, and D. L. Rudnick, 2009: The vertical structure of shadow-zone arrivals at long range in the ocean. *J. Acoust. Soc. Am.***,** **125,** 3569-3588. [published, refereed]

Cole, S. T., D. L. Rudnick, and J. A. Colosi, 2009: Seasonal evolution of upper ocean horizontal structure and the remnant mixed layer. *J. Geophys. Res.* [submitted, refereed]

Van Uffelen, L., P. Worcester, M. Dzieciuch, D. Rudnick, and J. Colosi, 2009: Effects of upper ocean sound-speed structure on deep acoustic shadow-zone arrivals at 500- and 1000-km range. *J. Acoust. Soc. Am***.** [submitted, refereed]

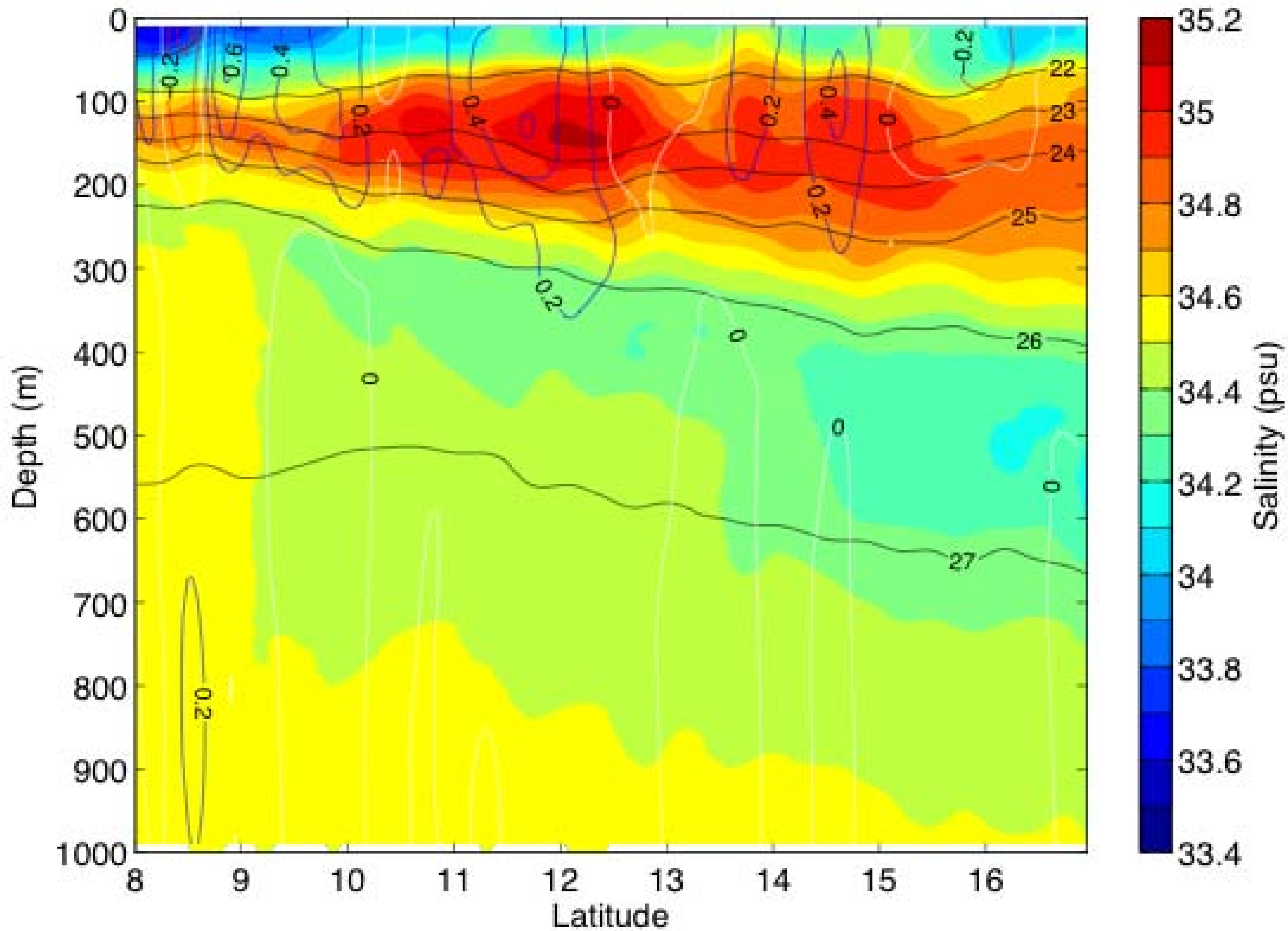

Figure 1. A section along 134°20'E across the NEC. Salinity is shown by color shading, potential density by black contours (interval 1 kg m^{-3}), and geostrophic velocity by color contours (zero contour white, westward contours blue, eastward contours red, interval 0.2 m s^{-1}). The section is derived from glider dives at about 6 km spacing. The data is then objectively mapped using a Gaussian autocovariance with a 50 km decorrelation length. Geostrophic velocity is calculated from the mapped data by combining the measured depth-average velocity and the horizontal gradient of the geopotential anomaly.